# Delivering Protons to the Antiproton Source after the Tevatron Collider Era

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## Abstract

A way to deliver 8-GeV protons from the Booster to the Antiproton Source via existing enclosures and beam lines is described. By using the existing 8-GeV line and most of the Recycler as parts of the beam path, the scheme avoids the need for new civil construction and new beam transport lines. In this way, as soon as the Tevatron Collider era is over, the Antiproton Source can be rapidly transformed into a very useful pair of proton storage rings for various applications.

## Introduction

When the Tevatron Collider era comes to an end, resources presently devoted to that program will become available. In particular, the three 8-GeV storage rings presently used for antiprotons (the Recycler, the Debuncher and the Accumulator) can be used for other applications. This note describes a way to deliver 8-GeV proton beam from the Booster, via the Recycler, to the Accumulator and the Debuncher using existing beam transport lines without the need for new civil construction.

The delivery of intense proton beams for neutrino experiments is a high-priority element of the Fermilab physics program for the foreseeable future. Plans to use the Recycler and the Accumulator to increase the intensity of proton beams from the Main Injector (MI) for neutrino experiments have already been developed. The scheme described in this note would not interfere with those neutrino plans but would in fact work synergistically with them while creating additional physics opportunities.

One such opportunity is a muon-to-electron conversion experiment [1]. Such an experiment would use slow spill from the Debuncher; the desire to deliver protons to the Debuncher for such an experiment was in fact the original impetus for the development of the ideas described here. Another attractive application would be providing proton beams for testing concepts and components such as those for a neutrino factory or a lepton collider based on cold muon beams.

## Overview of Future Neutrino Plans

A brief overview of accelerator aspects of future neutrino plans will provide context for the scheme proposed here. There are two ideas, presently called NOνA [2] and SNuMI [3]. The accelerator part of the NOνA project proposes to use the Recycler as a proton accumulator to slipstack 12 Booster batches for the MI. The SNuMI proposal would use the Accumulator to momentum-stack three Booster batches at a time and then transfer six of these "super-batches" to the Recycler, which would still function as an accumulator for the MI. Since it is likely that NOνA and SNuMI will be implemented sequentially, this note describes in some detail how the scheme would work with NOνA. Subsequently, the implications and modifications for SNuMI are briefly discussed.

In the NOνA project, protons from the Booster will be transferred along the MI8 Line to the Recycler. Twelve Booster batches will be slipstacked in the Recycler, transferred to the MI, accelerated to 120 GeV, and delivered to the NUMI target. The MI acceleration cycle is 1.33 sec or 20 Booster cycles long. In NOνA there are eight Booster cycles that are not used. This note describes a plan to transfer the Booster beam not used by NOνA into the Antiproton Source. Figure1 shows (in red) the proton beam path envisioned by this note. With suitable modifications, the beam can circulate in either direction in the Antiproton Source; presumably the choice of direction will be made after detailed analysis of the pros and cons. Figure 2 shows the time line for the NOνA program. Note that the Recycler Ring is empty for as many as eight Booster cycles during each MI cycle.

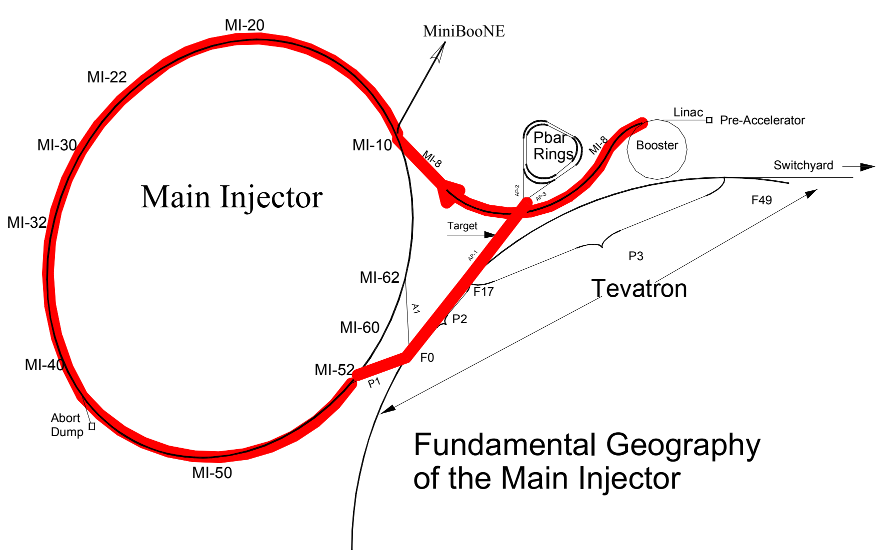


Figure 1. The layout of the Proton Source and Main Injector complex, showing (in red) the beam path proposed here.

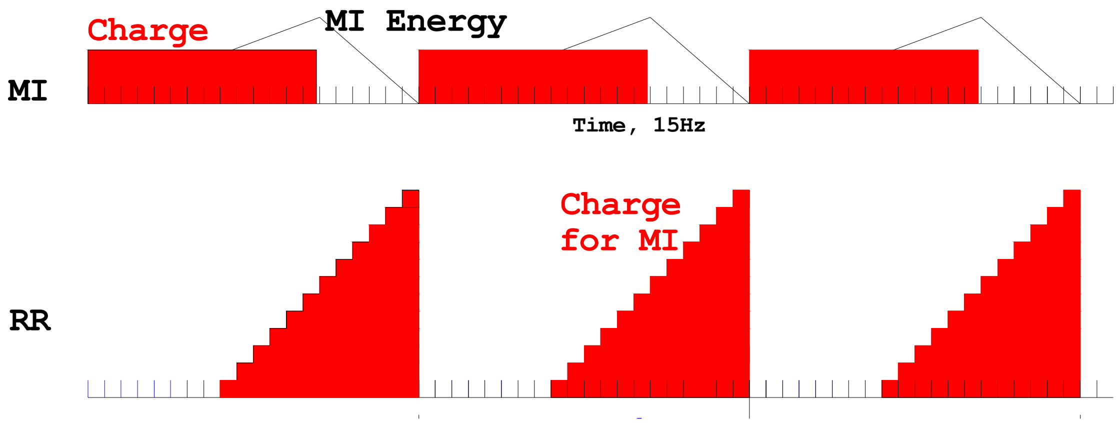


Figure 2. The time line for the NOνA project, showing proton beam in the Main Injector and the Recycler Ring.

## Recycler and P150 Transfer Line Modification in the NOνA era

At present the MI8 line transports beam from the Booster to be injected into the MI at location MI-100 in the MI-10 straight section. The NOνA plan assumes that the MI8 beam line will be connected directly to the Recycler at the same location. In the scheme presented here for the NOνA era, the beam destined for the Antiproton Source would take the same path into the Recycler. Note that during this time the Recycler is otherwise empty.

The scheme needs a new extraction point that will connect the Recycler with the P150 line. We propose to extract from the Recycler at MI52 just after the Recycler quad called Q552B as shown in Figure 3. The space available between the correction dipole after Q552B and the next beam element is more than 5.8 meters.

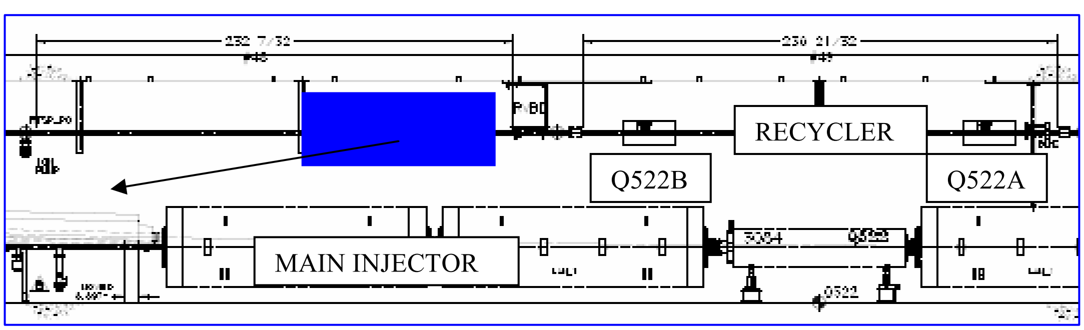


Figure 3. The extraction magnet is shown in blue in the Recycler at MI-52.

Figure 4 shows the injection point in the P150 line between quads q702 and q703, near q703. The distance between these two quads is about 16 meters. The distance from extraction in the Recycler to injection in the P150 line is about 44 meters. The elevation change is about 0.8 meters. This means that the bending angle downward is about 20 mrad. As can be seen from Figure 3 and 4, this angle is more than adequate to clear the magnetic elements in the Recycler after extraction and the magnetic elements in the P150 line before the injection point. Subsequently, the proton beam would take the route presently used when “reverse protons” are sent to the Antiproton Source.

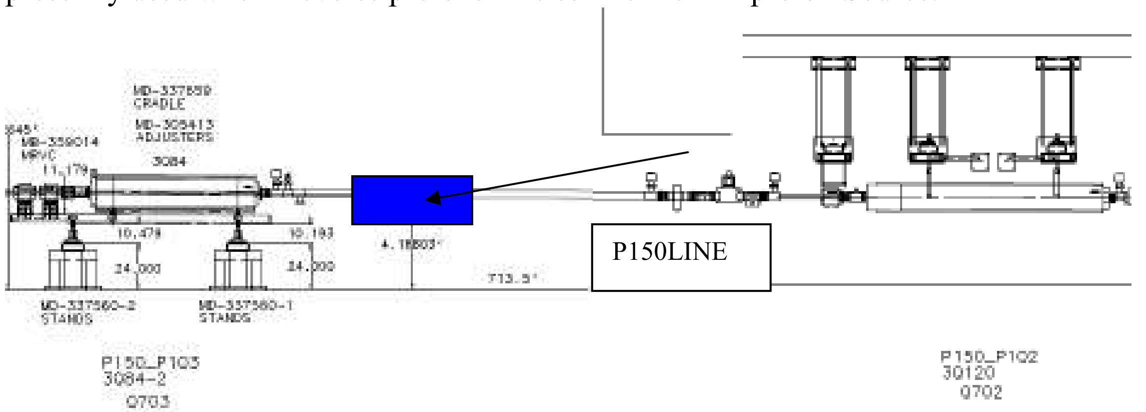


Figure 4. The new vertical bending magnet for injection in the P150 line is shown in blue.

For example, two bending magnets left over from the Fermilab Electron Cooling Ring Project can be used for this purpose. A field of 5 kG will bend the 8 GeV beam by about 22 mrad. Some of the parameters of these magnets are listed in Table 1.

| | | |
|---|---|---|
| Field strength | 4.3 | kG |
| Magnet length | 48 | in |
| Magnet gap | 3.25 | in |
| Field aperture | +- 4 | in |
| Current | 711 | A |
| Inductance | 0.01 | h |
| Resistance | 0.025 | Ohm |
| Voltage drop | 17.8 | V |
| Power | 12.6 | kW |
| Outside dimension | 10 x 22 | in |

Table1.

During NuMI operations for NOνA, with twelve Booster batches going to the MI, there are eight Booster batches potentially available for other applications. The actual number that can be delivered to the Antiproton Source by the scheme described here will depend on how long the twelve batches destined for the MI remain in the Recycler and how long it takes to ramp the extraction dipole up and down. For example, ramping the magnet up and down in less than 66ms can be achieved using a voltage of about 250 Volts from a Transrex power supply. The corresponding magnet in the P150 Line can run at a field appropriate for 8 GeV during this mode of operation of the accelerator complex; it can ramp slowly to a higher value when it is occasionally required to transmit 120 GeV beam from the MI.. Figure 5 suggests that two quadrupole magnets will be needed between the two vertical bends.

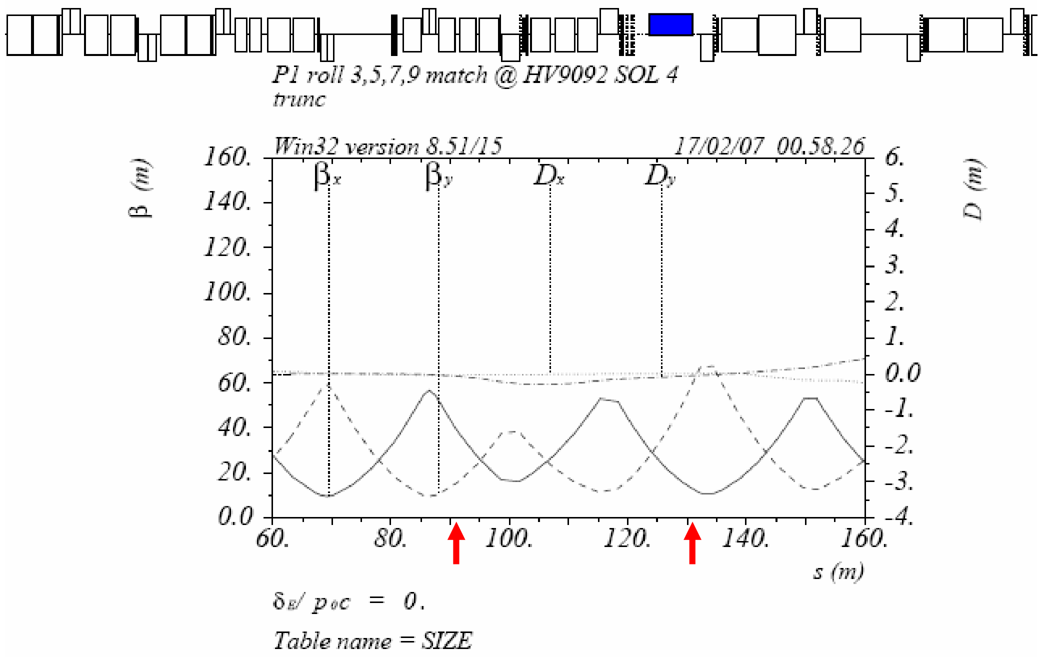


Figure 5. The MAD [4] output for the P150 line. The red arrows indicate the approximate separation between the two dipole magnets, with the first being in the Recycler and the second in the P150 line as shown.

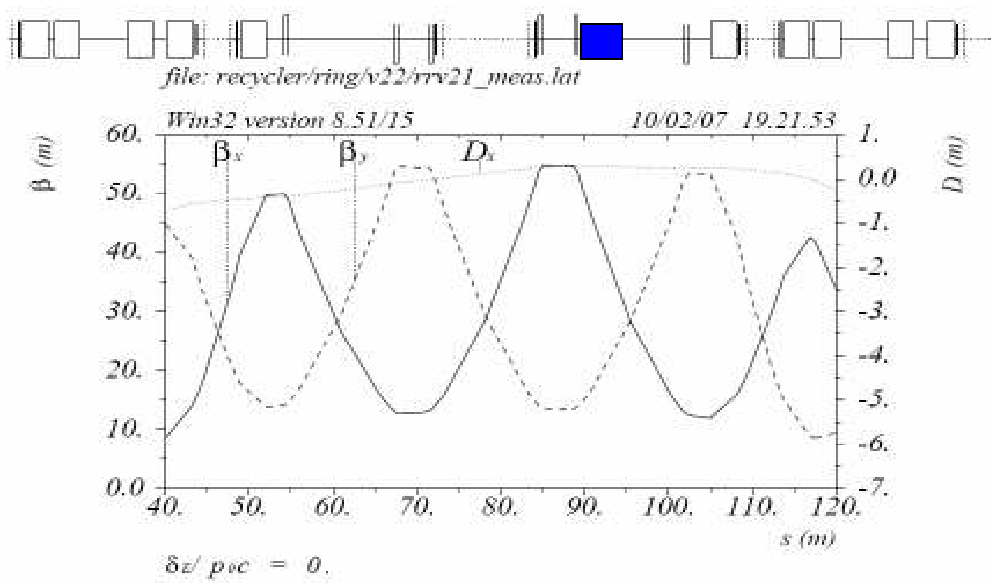


Figure 6. The output of a MAD run for the Recycler.

The Twiss parameters of the beam at the extraction point from the Recycler and at the point of injection into the P150 line are listed in Table 2.

| | Alfa_x | Beta_X | Alfa_y | Beta_y |
|---|---|---|---|---|
| From Recycler | 2.4 | 53.1 | -0.8 | 14.1 |
| To P150 Line | 0.6 | 11.1 | -2.9 | 66.3 |

Table 2.

These numbers were used to find positions and quadrupole strengths to match the Recycler beam to the P150 Line. The vertical dispersion of about 0.8 meters generated by the vertical dogleg is not expected to be a problem but could be mitigated by dispersion matching if necessary. Figure 7 shows a Trace3D [5] run with approximate positions of the quads. The quads are 0.5 meter long and have gradients of 4.5 and 4.7 T/m. These two quads are not demanding and should be easy to build. It may also be possible to use two pairs of permanent magnet quads (RQEC and RQED type) left from the Recycler project. Table 3 lists the names, fields and number of available quads.

| series | Integrated quad strength (T-m/m) | Number |
|---|---|---|
| RQEC | -2.240 | 5 |
| RQED | 1.697 | 2 |

Table 3.

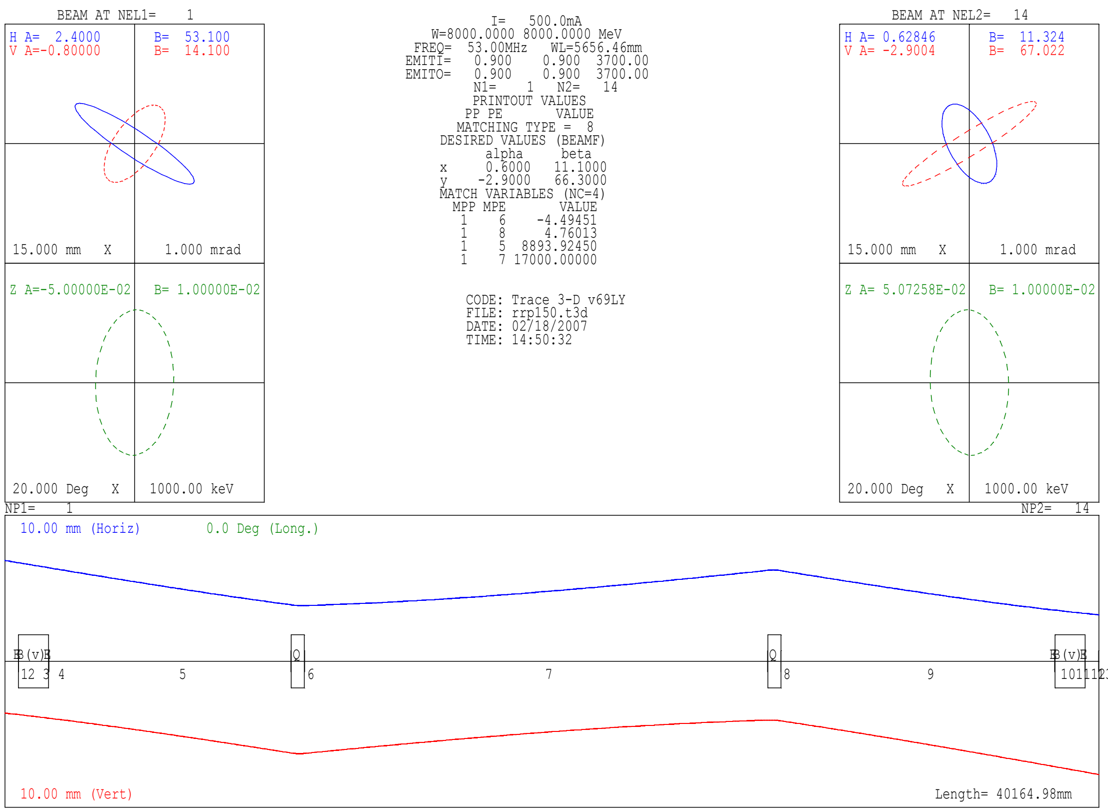


Figure 7. The Trace3D output for the beam line connecting Recycler and P150 line.

## Implications for SNuMI

SNuMI requires proton batches from the Booster to be momentum-stacked in the Accumulator. The scheme described here would have the considerable advantage of allowing the commissioning of the relevant systems and the demonstration of stacking of multiple batches in the Accumulator before the rest of the SNuMI project is implemented. In the SNuMI era, the extraction magnet in the Recycler would have to be replaced with a system of kickers and Lambertson magnets. That way, the Recycler could still be used as a transfer line even though it is partially full with as many as five "superbatches". In other words, this scheme would obviate the need for a new transfer line in a new tunnel between the Booster and the Accumulator for SNuMI. Since SNuMI would use 18 Booster batches and the minimum Main Injector cycle time is 20 Booster cycles, there would then still be two "free" batches available for other applications.

## Acknowledgments

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